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US CLIVAR Science Applications

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This issue of *Variations* contains several articles that build upon a line of thinking introduced at the 2014 US CLIVAR Summit plenary session entitled, "Progress and Prospects for Connecting Predictions, Applications and Decision Making." By improving understanding of physical climate and ocean phenomena, US CLIVAR research has the intrinsic power to benefit society, and by collaborating "with research and operational communities that develop and use climate information," as mentioned in the US CLIVAR Science Plan, the research community can mainstream the benefits of research insights.

Applied science researchers and organizations need and use US CLIVAR research when they work directly with decision makers. Thus, these researchers and organizations can provide important feedback to the US CLIVAR community, by helping identify research gaps and relaying the needs articulated by decision makers. Moreover, climate intermediaries and their clientele benefit from knowledge of the latest scientific advances, which can be used in decision-support tools and management practices.

Jacobs reflects on the deliberate design of the recent National Climate Assessment to support decision making: by bridging

Lessons from the National Climate Assessment on science translation and boundary organizations

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Scientific assessments explore the state of knowledge on a given topic, and are often used as part of science program evaluations to understand progress towards defined goals. In the case of the National Climate Assessment, there is a federal statutory requirement to integrate, assess, and analyze information that is developed by the US Global Change Research Program "at least every four years" (Global Change Research Act 1990), but also to identify current and future impacts on a wide variety of sectors and to discuss associated uncertainties.

There have now been three National Climate Assessments, one published in 2000 at the end of the Clinton Administration; one published in 2009 just past the end of the Bush administration; and one released in May 2014 (www.nca2014.globalchange.gov) that was produced during the Obama Administration. All of these assessments depended heavily on both federal and non-federal experts, but the Third National Climate Assessment (NCA3) process was explicitly focused on building long-term capacity to produce global change assessments that are useful not only to researchers and federal program managers, but also to policy makers and resource managers in a local, regional, and state decision-support context (Melillo et al. 2014).

Regardless of how many years it has been since the last national assessment, sorting through thousands of new papers that have emerged over the intervening years since the last one, and integrating and evaluating those findings to assess what is currently known and what is still uncertain, are difficult tasks. Adding to this challenge is the need to bring knowledge to the fore that is constantly being generated by major new investments in observing systems, modeling, and analysis, while also interfacing with and navigating through the processes and products of the Intergovernmental Panel on Climate Change. If that was the extent of the assignment, conducting a National Climate Assessment would be a daunting task for the scientific

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gaps in climate science communication between research experts and decision makers, by developing knowledge networks of scientists and stakeholders to address risks related to climate change, and by aiming to address issues related to temporal and spatial scales of decisions. Prairie and Raff address the climate research and information needs identified by federal water management agencies. These include increased forecast skill, improved precipitation and snow monitoring, and more detailed metadata on forecast development, skill, and reliability. Webb and co-authors use a case study from California's Russian River Basin to describe ways in which improved predictive understanding and research to enhance forecasts, on timescales from days to decades, can inform water management decisions and save water to meet multiple dry season water resource demands. And in an article on challenges in producing actionable science, I argue that in order to unlock the full potential of US CLIVAR basic research, and shorten the time from insight or innovation to application, the US CLIVAR research community has opportunities through work with intermediaries in the climate services community.

Collectively, these articles demonstrate ways in which US CLIVAR can work toward making the key research insights of the community more readily applicable to society's needs.

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community. But experience has shown that the decision to build products that are "salient, credible, and legitimate" (Cash et al. 2004) to stakeholders requires their active engagement[1], so the bar for a report that is "useful" in a decision context is even higher (Eden, 2011, Kirchhoff et al., 2013).

Multiple authors have noted that the potential to truly engage stakeholders in scientific discussions involves significant transaction costs (Cash et al. 2006; Buizer et al. 2010). Often there is a need for capacity building, to ensure that the stakeholders are able to meaningfully engage in discussions, especially to help navigate conversations that require an understanding of underlying scientific principles. In many such discussions, the "experts" use acronyms and disciplinary jargon that are very hard to navigate for the uninitiated (Jacobs et al. 2005). True engagement with stakeholders implies a two-way conversation, where scientists are also learning (Dilling and Lemos 2011). This often takes conversations in surprising new directions and may require significantly more time than originally allotted. Further, the framing of research questions may need to be adjusted in order to ensure that the fundamental approach is meaningful to all parties in the discussion. The time and resources needed for true engagement and building trusted relationships is often surprising (Jacobs et al. 2010).

Perhaps more noteworthy in this discussion is the need to ensure that scientists understand how and why stakeholders might want to use their information, and in particular, the 'decision context' within which the information might be used. This is particularly important where decisions are made within institutions (government, private, etc.) where the options are constrained by resources, training, regulations, or perceptions (Jacobs et al. 2005; Christoplos et al. 2009). In short, virtually all decisions are constrained by considerations that may not be evident at first glance to scientists who have spent much of their lives in laboratories, operating models, or analyzing data.

In recognition of the challenges associated with extraordinary complexity in global change science itself, and the often highly-tailored information requirements of particular kinds of stakeholders, an array of "science translators" has emerged in both the private and the public sector. A good example of private sector science translators is the range of consultants and in-house advisors that now support major agribusiness corporations. These experts take government-produced climate information and tailor it for particular decision contexts, and their livelihoods depend on their inside knowledge of how commodity markets work, how global markets operate, how crop insurance and financing affect planting decisions, etc. – as well as how seasonal to interannual climate information may be useful in optimizing profit.

In the public sector, a different set of translators has emerged, often within programs that are explicitly designed to help people navigate the array of available climate and weather data. Examples of these "boundary organizations" (Guston 2001) are the NOAA Regional Integrated Sciences and Assessments program, the Climate Science Centers and Landscape Conservation Cooperatives sponsored by the Department of the Interior, and the newly-created "climate hubs" of the US Department of Agriculture. Each of these networks is at least loosely affiliated with universities and research centers, and each exists to facilitate the connections and/or translate scientific findings in specific regions and within particular subject areas between research and

[1] For the purposes of this discussion we will assume that stakeholders are a broad range of decision-makers (which can include scientists and program managers) who could potentially use the scientific information produced through assessments.

applications. The recognition that decision-support science needs vary dramatically from one location to another and one sector to another is fundamental to connecting science and decision-making. The adage "place matters" is an important component of providing useful information at "decision scales" (e.g., within watersheds, utility service areas, government jurisdictions). In addition, the relevance of the time scale of decisions (e.g., seasonal decisions about managing water supplies in reservoirs versus long-term decisions about where, when, and whether to build the reservoir to start with) has emerged as a major consideration in providing useful decision support. Finally, understanding what the possible value of information is – versus the cost of providing it – when providing decision support has been emerging as a critical consideration over the past decades.

In summary, years of experience have now shown that it is really not possible to transfer knowledge about managing risk and using climate information on a wholesale basis – there need to be local investments in people who are "science translators" or "boundary spanners" who can help to efficiently bridge the gap between science and decision-making (McNie 2007). These people are "process" experts who may or may not have formal training in science, but have emerged as good communicators and facilitators (Cash et al. 2006).

The foundations for building the NCA3 were based on the building blocks described above, all relatively fundamental principles about connecting science and decision-making. The explicit goal of the NCA3 was "to enhance the ability of the United States to **anticipate, mitigate, and adapt** to changes in the global environment," and the vision adopted by its advisory committee was "to advance an **inclusive, broad-based, and sustained process** for assessing and communicating scientific knowledge of the impacts, risks, and vulnerabilities associated with a changing global climate in support of decision-making across the United States" (Melillo et al., 2014). Clearly, there was a need to bring what was already known about decision support to the fore in the NCA3 process. During the design of the NCA3, decision support itself became an assessment topic at the request of many private sector interests. Consequently, new chapters were added to the NCA3 outline assessing the state of knowledge/action in Adaptation, Mitigation and Decision Support. There were multiple ways in which ideas about science translation, coproduction of knowledge (Jasanoff 2004; Lemos and Morehouse 2005), and boundary-spanning were integrated into the design of the NCA3 itself. First, in the selection of members of the (60 member) federal advisory committee, the National Assessment Development and Advisory Committee (NCADAC), there was an explicit effort to include people who had been engaged in the science translation process, science communications efforts, and the design of boundary-spanning institutions like the NOAA RISA program. Several of these people were included in the Executive Secretariat of the NCADAC and played major roles in the overall design and management of the NCA3.

Second, in choosing the membership of the author teams, the NCADAC deliberately brought together multiple sources of knowledge, ranging from research to applications to management. In addition, there was an effort to include representatives from government (federal, state, and local), the private sector, academia, NGOs, and on-the-ground managers as well as "new faces" (people not involved in previous assessments) on the chapter author teams. The tacit knowledge that came from the non-academic partners in this process was critical to identifying priorities for the team to address, and also resulted in new sources of data, observations, and experience that might not otherwise have been available through a standard literature review. These new "knowledge networks" (Bidwell et al. 2013), were created deliberately, in part to build an integrated community of scientists and stakeholders who could work together to manage risks and opportunities associate with climate change.

Perspectives that have come from knowledge networks and social network analysis also informed the initial selection process for authors, but more importantly, the development of the engagement strategy for NCA3. The strategic plan for the engagement effort used a "network of networks" approach to building the National Climate Assessment Network, known now as NCAnet. Professional societies, advocacy organizations, non-governmental organizations, and other kinds of networks were identified as possible candidate members for each region, sector, and topic. They were contacted to see if they were interested in engaging with the NCA3 to support the efforts of the assessment process and/or to share its findings with their memberships/constituencies. This effort had a relatively modest beginning, but now includes more than 150 organizations (about 3 times the original group) who have self-identified and chosen to engage with the NCA activities. NCAnet played a major role in the successful strategy for sharing the NCA3 report very broadly and has continued to meet to amplify the outcomes through a variety of projects.

Lessons learned in boundary spanning activities (Jacobs et al. 2005; Lemos et al. 2014) were particularly important in managing the activities within the author teams, and many of these lessons were reinforced as the teams moved through various stages in the assessment process. For example, it was very clear to assessment staff that teams that were led by experienced facilitators, on average, had more interpersonal interactions and more opportunities to integrate multiple kinds of knowledge and perspectives than other teams. This reinforces the notion that the "boundary" between scientists and decision-makers or policy makers needs to be actively managed to make sure that the perspectives and contributions of all of the participants are respected and considered, especially where there may be differences in language or culture that need to be overcome.

As an exercise in capacity building, it was clear from the early days of the NCA3 that building a collective vision of what was to be achieved, and having non-federal participants involved in developing the strategic plan and the assessment methodologies from the beginning, were critical to the ability of participants to engage in a meaningful way in the conversations. In addition, jointly developing the assessment methodologies for a variety of fundamental activities (data management, use of scenarios and models, valuation approaches, vulnerability assessments, development of indicators, etc.) helped to build community around the otherwise highly distributed approach to this NCA process. Although there is a great deal still to be learned, many of the lessons that originated in efforts to connect science and decision-making in the "real world" were amplified in the experience of the NCA3.

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Monitoring, forecasting, and information use and needs for informing water management

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The water resource community relies on skillful seasonal forecasts coupled with operations models to manage–often conflicting–basin resources. Adapting to future climate variability and change impacts requires capabilities in hydroclimate monitoring, short-term prediction, and application of such information to support contemporary water management decisions. These needs were identified in a report, Short-Term Water Management Decisions: User Needs for Improved Climate, Weather, and Hydrologic Information, published in early 2013 by the Bureau of Reclamation and the US Army Corps of Engineers (USACE) with the National Oceanic and Atmospheric Administration. The needs are further motivated by potential climate variability and change impacts on water resources, such as ensuring the present understanding and modeling of precipitation and snowpack, which strongly influence seasonal prediction skill, can adapt along with changes in hydroclimate variability and change.

The report identifies how federal, state, local, tribal, and non-governmental organizations and agencies are working together to identify and respond to the needs of water resource managers in the face of climate variability and change. It outlines user needs and gaps shared across four categories: monitoring products, forecast products, understanding and using information products, and information services. These needs and gaps identify opportunities to enhance monitoring, forecasting, and the understanding and deployment of this information, which are critical for water operations and basin management. The short-term water management needs identified in this document are based on a "use and needs assessment" conducted with Reclamation and USACE water managers at all Reclamation regions and USACE divisions. The assessment categorizes information supporting short-term water management as either a monitoring or a prediction (forecast) product, where monitoring products are observations of the current or previous state of the hydroclimate system, and forecast products are projections of the future state of the hydroclimate system. The responses from the use assessment are synthesized into statements of needs that will inform efforts to develop technologies, scientific capabilities, and operations or practices to meet these needs.

Need statements presented in the following sections synthesize responses about users' experiences with new sources of hydroclimatic information, and they reflect direct statements of product needs. These statements and their associated text are taken directly or paraphrased from Raff et al. (2013).

Monitoring product needs

Monitoring product needs (Table 1) are found to focus primarily on observations of precipitation, snowpack, and streamflow. The needs emphasize the preservation and expansion of existing monitoring systems, which include US Geological Survey gauging stations, snow measurement networks, and rainfall gauges. These monitoring systems are identified as being critical to current

Sub-Category	Need Statement
General	Sustained support for monitoring networks that provide observations of weather and hyrologica conditions.
Precipitation	Expanded networks of weather stations in water management regions that are currently served by relatively low station density.
Snowpack	More interactive snow analysis products characterizing basin-distributed snow-covered area and snow-water equivalent.
	Expanded networks of snow-observing stations in the Central and Eastern United States.
Streamflow	Preserving and expanding networks of streamflow observations with a focus on streams and rivers that are currently ungauged.

Table 1. Monitoring product needs statements by sub-category.

and future short-term water management decision-making. Monitoring systems also received the highest priority when ranked by importance as part of the review process by other federal and non-federal reviewers. Under the precipitation sub-category, operators specifically cited needs in the Desert Southwest and Great Plains, both areas with sparse station density. In the snowpack sub-category, operators requested more interactive tools to visualize and interact with available observations. An emphasis on the importance of preserving gauges with long histories as well as historical streamflow information was expressed. Improving streamflow measurement and data networks, and developing more cost-effective measurement technologies, would also support longer-term efforts focused on climate change and reducing water resource vulnerabilities.

Forecasting product needs

Forecast products identify water management needs (Table 2) with respect to anticipating future climate, weather, and hydrologic conditions. A need was expressed to expand the geographic coverage of forecast products that aren't currently available for all regions, as well as develop new products that present a suite of hydroclimatic variables or parameters (e.g., evaporation from open water bodies, soil moisture, water temperature and quality, and ecosystem responses). Efforts to address the general sub-category and the last 4 needs listed in Table 2 would contribute to improved drought anticipation and preparedness -- a critical area needing advancement. A surprising request expressed interest in having seasonal runoff volume, or "water supply," forecast in the Great Plains, Great Lakes, and South Atlantic regions. Typically these forecasts have only been provided in snowmelt-dominated regions. A final suggestion was to connect such forecasts to larger-scale state of climate variability (e.g., El Niño or La Niña states of the El Niño Southern Oscillation.

Sub-Category	Need Statement
General	Enhanced suite of hydrologic predictions spanning lead-times of days to seasons and consistent with the continuum of weather to climate forecast products.
Precipitation, supporting fine resolution outlooks	More reliable quantitative precipitation forecasts (QPF) on lead times of hours to days.
	Improved precipitation forecasts for land falling storms in coastal areas.
Streamflow, supporting fine resolution outlooks	Enhanced streamflow predictions on lead times of hours to days, particularly during storm events.
Streamflow, supporting medium resolution outlooks	Enhanced streamflow predictions on lead times of days to weeks, particularly during the snowmelt season.
Runoff volume, supporting coarse resolution outlooks	Improved anticipation of runoff volumes during lead times of months to seasons.
Water level	Enhanced prediction products characterizing potential water levels during storm events.
Other hydroclimate	Multi-variate suite of climate to hydrologic predictions that comprehensively characterizes the state and evolution of basin hydrologic conditions on lead times of days to seasons.

Table 2. Forecasting product needs statements by sub-category.

Understanding and utilizing information products in water management

How products are understood or interpreted and then used for decision-making (in contrast to improvement of product information covered in the previous two sections) is the focus of need statements relating to understanding and using information products (Table 3, next page). Several operators expressed "information overload" as a challenge when assessing available information and deciding how products should be used. A better understanding of how information fits together and providing expert guidance would help address this identified need. Another aspect is developing training resources targeted for nontechnical stakeholders. Operators suggested two areas of focus. One area would be to explain hydroclimate information products, and their potential synthesis, relative to various water management situations, how products are presently used in reservoir operations, and how their use relates to the needs of various water customers. A second area would inform water managers of the principles associated with applying probabilistic forecast information to support risk-based decision-making. The second area could include developing

Sub-Category	Need Statement
Information on product development and qualitative attributes	More detailed meta-information describing product skill, reliability, and development.
Information synthesis	Guidance on how to synthesize available hydroclimate information relative to its collective applicability to water management situations.
Education on water management and forecasting principles	Training resources on water management principles spanning multiple time-scales.
	Training resources on probabilistic forecasting principles and risk-based decision-making.

Table 3. Understanding and using information products in water management needs statements by sub-category.

a common "risk" language with definitions and metrics, and further highlight the importance of understanding rare outcomes and explaining that a missed outcome by a probabilistic forecast is not necessarily an indication of poor skill.

Information service enterprise

The last category of needs draws attention to the private-public sector interface that provides and utilizes hydroclimatic information for short-term decision-making in water resources management. Information service enterprise needs identified in Table 4 incorporate more frequent improvements and updates of prediction models, including the impacts of new runoff drivers such as characterization of dust on snow. A more difficult need to address, because of the diversity of the water management community and it modeling system, is developing more accessible product dissemination formats for direct use within existing water management tools.

Sub-Category	Need Statement
Product maintenance	Support for product maintenance and evolution to accommodate new observations and research developments.
Product format	Development of product deployment formats that interface more readily with information systems commonly used in the water management community.

Table 4. Information service enterprise needs statemens by sub-category.

Summary

The need statements reflect the synthesis of information identified by USACE and Reclamation water resource managers through a use assessment distributed to all USACE divisions and districts and all Reclamation regions and area offices. The results of the assessment indicate a tremendous diversity of product utilization and the needs of different resource managers, based in part on different geographical and hydrologic systems in which they operate, as well as different mission responsibilities and authorities. There are numerous opportunities to utilize new and better information, from more skillful forecasts to better management of the information that is already produced. There are, however, constraints within water management institutions that limit the ability to produce and use information, which guides the needs identified within this document.

Many of the needs expressed in the Raff et al. (2013) assessment strongly relate to the US CLIVAR Science Plan to integrate improvements in the understanding of processes that contribute to climate variability and change, with efforts to improve climate simulations and predictions, and to better understand the limits of predictability (US CLIVAR SSC 2013). Integration of process understanding with modeling and prediction is critical to meeting Reclamation's and USACE's needs for improved forecasting and a suite of predictions, at multiple time scales, which can characterize the state and evolution of basin hydrologic conditions.

US CLIVAR efforts to work with various scientific communities to develop improved monitoring networks can help improve the development and evaluation of climate simulations and predictions for western US basins that are dependent on winter precipitation. US CLIVAR science outputs could help refine forecasts that are dependent on nuances in ocean-atmosphere interactions. Moreover, increased US CLIVAR emphasis on extreme events and interactions between polar and mid-latitude atmospheric circulations would help inform Reclamation and USACE hydrologic forecasts in coming years

The new US CLIVAR Science Plan focuses on communication of climate research, with emphases on knowledge exchange with applied climate and hydrology research communities and improved communication of uncertainty. These efforts mesh well with needs articulated in Tables 3 and could support development of requested guidance and training materials.

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Environmental Intelligence to support decision-making in California's Russian River Basin: A case study for wine, fish, water management, and the prediction of hydrologic events

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The episodic nature of precipitation on the West Coast of the US challenges the abilities of water resource managers to meet regional economic and environmental needs. Maximizing the availability of water stored in reservoirs to meet the full spectrum of potential uses in the West Coast's Mediterranean climate, with winter rains and dry, hot summers, is complicated by the multi-use of many reservoirs for both flood control and water supply. We present a case study of such challenges in the Russian River Valley, with a focus on Lake Mendocino. Lake Mendocino is one of two major reservoir projects used to manage water supply for the Russian River watershed. Lake Mendocino provides water for agriculture, municipal, and industrial uses, and to maintain required minimum stream flows. Minimum stream flows support both river-related recreation and fish habitat and passage for three salmonid species listed under the federal and California Endangered Species Act.

Another water management constraint involves the importation of water, since 1908, from the Eel River to the Russian River via a diversion tunnel associated with a hydroelectric facility. Lake Mendocino was designed assuming the historical levels of Eel River imports. In 2004, as part of a Federal Energy Regulatory Commission (FERC) relicensing of the facility, Eel River diversions were significantly curtailed; thus, further impacting the reliability of Lake Mendocino water supply. Prior to this event, more than 60% of annual inflow to Lake Mendocino was from the Eel River, while now this source comprises less than 30% of the total annual inflow.

We describe the research opportunities across weather and climate time scales to improve forecasts of the location and duration of extreme precipitation events with lead times from hours to days to seasons, combined with improved outlooks of the onset, severity, and durations of drought. Collectively, the development of a predictive understanding leading to more skillful and reliable forecasts has the potential to advance operational capabilities to provide the early warnings that are needed to implement Forecast Informed Reservoir Operations and, thus, be able to 'save some of this water' to meet multiple water resource demands during the dry season. We also identify a number of research opportunities to enhance forecast and prediction capabilities that have the potential to inform management practices, which could leave more water in the river and support efforts to restore threatened and endangered fish populations.

Background

A clear understanding of the context in which water resource management decisions are made in California's Russian River Basin is critical to inform use-inspired research to produce climate science-based knowledge that is readily understandable and immediately applicable. Understanding the annual cycle of decisions has proven to be a practical framework to clarify information needs and to identify entry points and opportunities for the use of advances in climate research (Ray and Webb 2015). We use this approach to identify opportunities and challenges for advances in climate research to produce actionable science that can be used to maximize the availability of water to meet a spectrum of potential uses in the Russian River Basin. In identifying opportunities and challenges, we focus on flood control, water supply, and vineyard and fisheries management decisions that could potentially benefit from improve use of climate information.

California's Russian River Basin watershed occupies an area of roughly 3846 km2—with steep terrain associated with hills and mountains making up approximately 85 percent of the watershed, and valleys the remaining 15 percent. The climate of the basin is dominated by the West Coast's Mediterranean climate, with a vast majority of the annual precipitation delivered in the form of winter rains. The persistence of dry, hot summers contributes minimal precipitation to the total annual rainfall. Annual average precipitation in the basin is 104 cm, with approximately 90 percent falling during November through April. Furthermore, this winter rainfall is concentrated in a handful of extreme precipitation events, with close to 80 percent of these events in the form of atmospheric rivers (ARs; Zhu and Newell 1998). ARs are narrow atmospheric corridors of concentrated moisture that supply significant amounts of tropical and low latitude moisture to the mid-to-high latitudes. The extreme rainfall from these ARs can be beneficial to water supply, but can also lead to devastating floods (Ralph et al. 2006). At the same time, the absence of a few or all of these extreme rainfall events over the winter rainy season can transition the basin into drought conditions. The flood-control and water-supply operational rules for these reservoirs do not allow for flexible and adaptive management to respond to the region's highly variable weather and climate.

The hydrology of California's Russian River Basin has been previously described in a report prepared for the Russian River Estuary Management Project (SCWA 2011). The two largest reservoirs in basin are Lake Mendocino and Lake Sonoma. The drainage area regulated by the reservoirs is approximately 15 percent of the total Russian River watershed. In the lower part of the main stem, during the wet-season, average daily flows greater than 1000 cfs persist from December through April, whereas dry-season average daily flows less than 300 cfs persist from July through October. Releases are made from the dams to meet downstream water supply requirements, minimum instream flow requirements, and to maximize storage. The impact of reservoir operations modulates flows in the Russian River by reducing the magnitude of peak flooding and increasing the dry-season minimum flows. Because most of the basin is unregulated for flood control, during extreme precipitation events releases from the reservoirs are either greatly curtailed or shutdown.

Water supply management practices include diversion of Russian River and Dry Creek flows, as well as water stored and later released from Lake Mendocino and Lake Sonoma. Water releases from storage are delivered to municipalities, where the water is used primarily for urban and rural residential, governmental, commercial, and industrial purposes, minimum stream flows, and agriculture. Flood control practices include maintenance of a flood pool to regulate the downstream impact of floodwaters. The reservoir dam operations are determined by a water control manual that prescribes release flows as a function of pool level, non-regulated flows in the Russian River, damaging flood stages downstream of the dam, and the current release schedule. Flood control operations are designed to store water during a flood event, then evacuate the flood control pool as quickly as possible to prepare for another extreme precipitation event The Russian River serves as an important source of agricultural irrigation directly and through groundwater withdrawals. In addition, during spring season frost events, vineyards withdraw water from streams or wells near the river or tributaries to spray vines to protect them from damaging frost. Sometimes water extraction can cause reduced stream flows that negatively impact aquatic species and ecosystems.

Recovery plans for threatened and endangered salmonid species include minimum and maximum stream flow as well as water quality requirements to support fish habitat and passage. Central California Coast steelhead are well distributed in the basin, spawn primarily in the tributaries, spend one to two years in the river basin followed by two years in the ocean, and can spawn more than once. California Coastal Chinook salmon spawn in the Russian River main stem and, after spending 10 months or less in the river, enter the ocean. Central California Coast Coho salmon are found primarily in the Lower River, and spawn in the tributaries. The Russian River Biological Opinion (NMFS 2008) involves both immediate and long-term actions to improve habitat and fish populations that will guide water management decisions to protect threatened or endangered salmonids. Near term actions to support recovery of these fish include:

- modifying minimum flows to improve rearing habitat for juvenile salmon and steelhead,
- increasing the frequency and duration of freshwater lagoon conditions,
- enhancing releases of cold water to support summer rearing conditions and fall adult Chinook salmon migration runs,
- managing ramping rates of releases to allow young fish to seek low flow habitat as velocities increase but not be stranded as flows decrease, and
- stabilizing the timing and volume of releases to improve water quality and turbidity conditions, as well as to provide reliable stream flow for endangered species.

CLIVAR research challenge

The improved prediction of hydrologic extremes across weather and climate time scales in the Russian River basin has the potential to enhance flexibility in reservoir operations for flood control while maximizing the availability of water for consumptive use and environmental services. Research is needed to better i) observe key physical processes, ii) provide the process understanding, iii) develop predictive capabilities, and iv) improve forecasts of the location and duration of extreme precipitation events, with lead times from hours to days to seasons, combined with improved outlooks of the onset, severity, and durations of extreme drought.

As noted by Dole et al. (2013), one needs to consider contributions across various weather and climate time scales to be able to both anticipate and predict hydrologic extreme events. On the timescales of long-term global warming trends and decadal or longer variability, potential predictability from can result from a regime shift to wetter or to drier conditions. At interannual to multiseasonal lead times, there can be shifts in the probability distributions towards wetter or drier conditions, but not necessarily an increased risk of hydrologic extremes. At a lead time of a season or two, a larger wetter/drier signal together with an increased probability of hydrologic extremes can develop in association with the emergence of the wintertime sea surface temperature pattern. This increased risk can persist through the winter, with some further increase in the probability of wetter/drier extremes for forecasts initialized with lead times of a month. At subseasonal timescales (a week to a number of weeks), large increases in the probability of extreme precipitation events, in particular, can greatly enhance risk of extreme flooding conditions. On time scales of hours to a few days, there can be regional to local increased risk for extreme precipitation resulting in high impact flooding events. The cumulative shift in an increased risk of hydrologic extremes across weather and climate timescales can both modulate and amplify the likelihood of wetter or drier conditions leading to increased possibilities of flood or drought impacts.

CLIVAR research opportunities to support decision-making in the Russian River Basin

Collectively, the development of a predictive understanding leading to more skillful and reliable forecasts has the potential to advance operational capabilities to provide the early warnings that are needed to implement Forecast Informed Reservoir Operations and thus be able to 'save some of this water' to meet multiple water resource demands during the dry season (Figure 1). Research opportunities to enhance forecast and prediction capabilities could inform management practices in the Russian River, leave more water in the river, and support efforts to restore threatened and endangered fish populations.

To "save some of this water" through improved early warning, a better understanding of large scale dynamics of extremes is needed to predict the timing of the next extreme precipitation event. A predictive understanding is needed to develop reliable and skillful hazard outlooks of extreme precipitation at 0 to 10 days, which would allow reservoir managers to avoid immediately evacuating water from the flood pool. Development of a reliable and skillful 8-day outlook of low risk of extreme precipitation, issued daily, could allow reservoir managers to retain water in the flood control pool on a day-to-day basis during the winter rainy season, as long as the risk remains low. On slightly longer timescales, a predictive understanding is needed to develop reliable and skillful late-winter subseasonal outlooks (15 to 45 days) of risk for extreme precipitation events could allow reservoir managers to hold additional water in flood pool space in the weeks leading up to the rule curve increase in reservoir storage for water supply at the beginning of March (Figure 1).

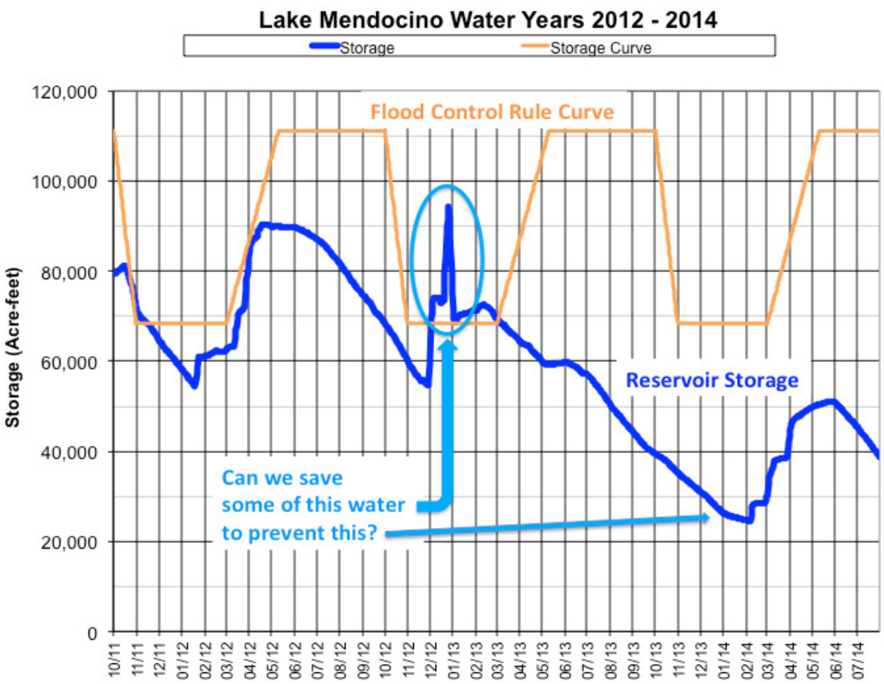

Figure 1. Lake Mendocino Reservoir storage and rule curve from 2011 to 2014.

To "save some of this water" through informed preparedness, there is a need to know the large-scale climate dynamics of extremes, in order to predict changes in extreme precipitation event risk. A predictive understanding is needed to develop reliable and skillful seasonal outlooks, at 3 to 6 months, of conditional risk of more or less extreme precipitation events over the winter/spring rain season; this would inform hedging strategies in managing flood pool space decisions to implement forecast-based operations. A diagnostic investigation into the relationships between large-scale atmospheric patterns and processes and rainfall events is needed to look at the extent to which year-to-year variations of extreme daily precipitation statistics over northern California are determined by sea surface temperatures or by sea ice forcing. A better understanding of key physical processes is needed to produce regional probabilistic estimates for drought recovery, given antecedent conditions, local climate, and climate predictions to explore the translation of more common precipitation estimates of recovery into regional indices of runoff. These can be used to infer the likelihood of reservoir storage recovery and return of full natural flow estimates to target ranges that are needed to inform management decisions for water supply, flood control, species preservation, salinity control, etc. A predictive understanding is needed to develop reliable and skillful multi-season to multi-decade outlooks of risk for more/less extreme precipitation and drought, in order to apply hedging strategies in managing water supplies, minimum flow releases, and consumptive uses.

To "make better use of saved water", an improved understanding of regional-to-local meteorological processes is needed to develop reliable and skillful site-specific short term frost forecasts and subseasonal-to-seasonal cold outbreak outlooks. These can be used to guide vineyard growers to reduce the use of water from the Russian River to spray their vineyards to protect the grape blossoms, or to rely on other methods, such as fans, to combat frost. A predictive understanding is needed to develop reliable and skillful 0 to 14 day precipitation forecasts and subseasonal-to-seasonal streamflow outlooks to guide hatchery releases to maximize vitality of native fish populations. A predictive understanding is needed to develop reliable and skillful subseasonal-to-seasonal coastal upwelling outlooks to guide management of native and hatchery fisheries.

To "make better use of saved water" to improve resilience and sustainability in the Russian River Basin, an improved predictive understanding is needed to provide reliable and skillful seasonal-to-decadal outlooks of the nutrient content of upwelled water; these can be used to help guide decisions in the management of native and hatchery fisheries. A predictive understanding is needed to develop reliable and skillful annual–to-multi-decadal outlooks of local sea level rise, to inform water supply requirements, in order to manage salt water intrusion in estuaries. A predictive understanding of the basin's coupled hydroclimate system is needed to develop reliable and skillful predictions of how variations in climate can impact surface flows, soil moisture, and groundwater storage. This understanding will, inform the sustainability of current reservoir systems and water management practices, in order to meet the full spectrum of water supply requirements.

Conclusion

We have identified a number of opportunities for CLIVAR research to produce weather and climate science-based knowledge that can be transformed to be readily understandable and immediately available to support decision-making to improve availability of water supplies and environmental outcomes—without diminishing flood protection or dam safety. The strategic use of observations can help to reduce uncertainty in the current understanding of key physical processes of weather and climate extreme hydrologic events impacting the Russian River Basin. Diagnostic explanations can help elucidate the role of critical local and external processes leading these high-impact, extreme hydrologic events and provide a predictive understanding of these events. The correct representation of these phenomena is critical for making accurate forecasts of high-impact hydrologic events across weather and climate timescales. Advances in scientific knowledge have the potential to ensure that decision makers—who are managing vineyards, fisheries, water supply and other critical resources in the Russian River Basin—have access to the best available information, in order to understand risks related to extreme hydrologic events, and thus 'save some of the water' to meet multiple water resource demands during the dry season.

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Opportunities for transforming US CLIVAR basic research to actionable science for managing climate risk

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Motivation for actionable science

"Living with, and adapting to, climate variability and change is an everyday reality." (World Meteorological Organization 2014). Extreme weather events in the United States, like Superstorm Sandy and Hurricane Katrina, and elsewhere on Earth, like Typhoon Haiyan, along with evidence of increased risks to low-lying countries, due to rising sea levels, sharpen the focus on needs to improve understanding of climate phenomena and predictions to better serve society. National Research Council studies note the need for timely, reliable, and understandable climate information to inform risk management decisions by state and local authorities, and insurance and investment decisions by private sector companies, public utilities, and individuals (NRC 2010).

Uncertainty and surprise are key aspects of managing risk and preparing for future climate and environmental conditions. Decision makers relying on climate science findings, predictions, and climate information must also know, or have confidence in, the science relating to factors and processes that underlie climate predictions and projections. These points were poignantly expressed by San Francisco Public Utilities' David Behar at the 2011 World Climate Research Programme (WCRP) conference, when he pointed out the need for actionable science, which he defined as "data, analysis, and forecasts that are sufficiently predictive, accepted and understandable to support decision-making" (Kerr 2011). Climate scientist Bruce Hewitson added that "we're drowning in data…[and] we're not very good at turning it into information." Thus, timely and reliable science-based information and communication of uncertainties, extremes, tipping points, and the limits to predictability, as well as assessments of confidence in forecasts and projections are necessary for the science community to fulfill its role in helping society prepare for changing climate conditions.

Global organizations, like the WMO and the WCRP, have formed guidance and implementation documents for developing climate services in order to begin addressing issues related to climate risk, vulnerability, and informing climate-sensitive decisions. The WMO's Global Climate Services Framework (GCSF) articulates overarching goals, which include mainstreaming the use of climate information in decision making and strengthening the engagement of providers and users of climate services. Not unlike the US CLIVAR Science Plan, components of the GCSF include observations, monitoring, research, modeling and prediction, in addition to efforts to develop a structured interface for climate researchers, information users, and information providers to interact (WMO 2014). In the United States, the US Global Change Research Program sets forth an ambitious goal for informing decisions, with elements that include facilitating meaningful engagements between scientists and decision makers, and providing access to relevant and accurate science (USGCRP 2012). It is through organizations and documents, such as these, that the call for actionable science is substantiated.

Challenges

The aforementioned needs, and ambitious goals and frameworks to address them, serve as flags around which climate science programs and government agencies can rally. But how, for example, might the US CLIVAR community participate in "meaningful engagements" and contribute to "mainstreaming the use of climate information in decision making?" The well-worn pathways for moving science findings to use, through publication of peer-reviewed papers and presentations at professional society, academic, or government agency meetings, are often referred to as trickle-down or Mode 1 research (vanKerkhoff and Lebel 2006; Kirchhoff et al. 2013). Mode 1 research is characterized as primarily knowledge driven, with low user participation in generating the motivation, research goals, and outputs (Kirchhoff et al. 2013). Even when the research is motivated by applied problems, a frequent pathway to users is through the loading dock – whereby data and products are heaved onto websites, with little or no input from prospective users about data formats, constraints in using information, website functionality, and other matters; this often renders useful knowledge and data products unusable by decision makers (Cash et al. 2006; Dilling and Lemos 2011).

The medical and public health science communities face similar challenges in dealing with research insights, time-sensitive risk management decisions, and communication with broad communities of information users. Research shows that the trickle-down approach requires more than a decade – up to 17 to 25 years (Brownson et al. 2006; Dougherty and Conway 2008) – for the diffusion of scientific insights to use by health practitioners and the public. To accelerate the research to use process, medical sciences have framed a process of translating science from research discovery ("bench-side") to use ("bedside") through iterative engagement between basic research scientists, applied clinical research scientists, public health practitioners and communicators, and the public (Dougherty and Conway 2008). The process is referred to as the "3Ts" of translating discovery (T1 "What works?") to clinical or efficacy testing (T2 "Who benefits?") to effectiveness of information use (T3 "How can we best deliver the findings or treatment?"). There is an imperfect, but relevant, parallel between the public health 3Ts and the issue of taking the basic insights generated by US CLIVAR scientists (T1) and making it into actionable applied climate science and products (T2) that is communicated well and used to inform climate-sensitive decisions (T3; see Figure 1). Some keys to the process for US CLIVAR include improved engagement and communication with intermediaries and organizations in the applied climate science community, and improved and enhanced mechanisms to address and learn about decision makers' basic and applied science needs.

The 3Ts model is still framed as a one-way, linear process, emanating from the science community to the user community. However in recent years, some science intermediaries have adopted a coproduction of knowledge model (see Jacobs, this issue; Cash et al. 2006; Ferguson et al. 2014). Coproduction of knowledge, or Mode 2 research (Kirchhoff et al. 2013), describes the collaboration of scientists and end users of scientific information, whose values and perspectives contribute to the knowledge generation, process, or product outputs of the collaboration. Examples of coproduced knowledge might include decision support models (e.g., U.S. Army Corps of Engineers' shared vision models), forecast products or graphics, and reports and assessments (Cash et al. 2006). The coproduction outputs have value for researchers, such as publishable papers, and for end users, such as information useful for decision-making. Coproduction of knowledge often builds capacity for the use of scientific outputs. This happens through social learning among participants, integration of research agendas, disciplines, and ways of knowing, and participation – whereby terms of engagement and research problems are co-defined and co-owned by scientists and decision maker participants (Dilling and Lemos 2011). Drawbacks of the coproduction process are that it is generally time consuming and can sometimes lack efficiency due to the dynamics of building relationships and trust among participants or from particularities of regions, sectors, or institutions (McNie 2012; Ferguson et al. 2014).

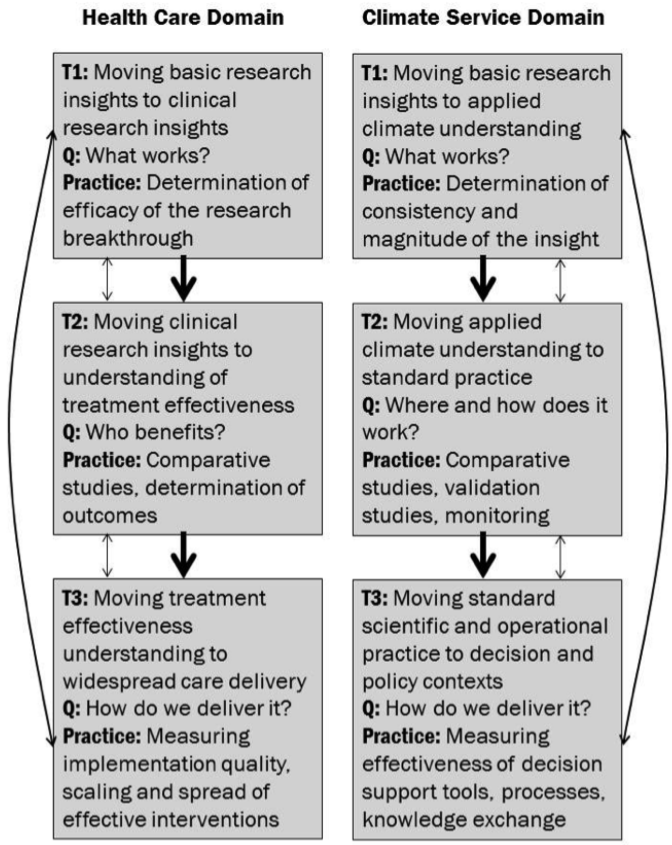

Figure 1. Parallels between health care translational research process and climate services research to decision-making process. Derived, in part, from Dougherty and Conway (2008).

Research to use via boundary organizations

In contrast to Mode 1 research, Mode 2 research is use-inspired or user-centric – byproducts of which are increased buy-in to the process and improved uptake, usability, and use of the science (Kirchhoff et al. 2013). This user-centered focus is at the core of climate service initiatives proposed by WMO (2014), the National Research Council (2010), and others. Table 1 describes the management of a boundary between the science and decision-making realms – of a participatory coproduction process – which requires attention to the varied pressures and metrics of accountability on both sides of the boundary (Cash et al. 2006; White et al. 2008). The boundary organization plays a key role in reconciling differences between the cultures of researchers and practitioners, through the functions of serving as a convener of interactions, a translator of specialized

Practitioner and Policy Domain	Boundary Organization Domain	Basic Science Research Domain
Decisions: resource management, policy, etc.	**Convening:** building relationships and trust	**Decisions:** research design, methods, theoretical basis, etc.
Accountability: public, board of directors, etc.	**Translation:** reconciling disciplinary jargon	**Accountability:** scientific peers, funding agencies, etc.
Contraints: rules of practice, funding, orgnaizational capacity, political pressures, laws, regulations, institutational culture, etc.	**Collaboration:** defining process, research agenda, outputs **Mediation:** reconciling, priorities and constraints, resolving conflict	**Constraints:** funding, organziational capacity, technological liminations, reward system pressures, institutional culture, etc.

Table 1. Elements of defining and managing the boundaries between science and decision-making domains, through a boundary organization and its key functions. Derived from Cash et al. (2006) and White et al. (2008).

disciplinary language, and as an honest broker in helping define a legitimate collaboration process for co-producing knowledge and resolving conflicts.

In the last couple of decades, the United States has experienced a proliferation of boundary organizations, which work to facilitate knowledge exchange and coproduction, data sharing, and to accelerate the use of science to inform decision-making. Such entities (Table 2), which reside in federal agencies, universities, and non-governmental organizations, could serve as prime intermediaries for US CLIVAR science, data, and insights. They could also facilitate institutional learning among the US CLIVAR community to better move climate science knowledge from the science domain ("supply side") to the decision-making or policy domains ("demand side"). Working with boundary organizations, and the agency managers and programs funding these organizations, would provide an applications pipeline for US CLIVAR science and feedback to the US CLIVAR basic science communities. Working through such intermediaries would also obviate the need for US CLIVAR scientists to add science communication and translation to a growing list of work-related tasks – though the opportunity to participate in these tasks would be available to willing researchers.

Getting to actionable science

Most research to date focuses on the application of seasonal climate forecasts or development of forecast-based decision support products through coproduction processes. For example, a new class of fire management decision-making products was developed through iterative interactions between seasonal climate forecasters and wildland fire professionals in a process mediated by NOAA Regional Integrated Sciences and Assessments (RISA) boundary organizations (Feldman et al. 2008; Lenart et al. 2005). The process required substantial trust building, knowledge exchange regarding basic and applied science insights on El Niño Southern Oscillation (ENSO) and other teleconnections, and forecast verification. For the fire practitioners to take the seasonal forecasts as credible, the process required a translational step to link synoptic patterns of geopotential heights with patterns of seasonal precipitation and temperature forecast probabilities.

Organization	Agency	Website
Climate Science Centers	DOI	www.doi.gov//csc/index.cfm
Cooperative Extension	USDA	www.csrees.usda.gov/Extension/
Landscape Conservation Cooperatives	DOI	www.doi.gov/csc/northwest/landscape-conservation-cooperatives.cfm
Regional Integrated Sciences and Assessments	NOAA	www.cpo.noaa.gov/ClimatePrograms/Climateand-SocietalInteractions/RISAProgram.aspx
Regional Climate Hubs	USDA	www.usda.gov/oce/climate_change/regional_hubs.htm
USA National Phenology Network	Multi-agency	www.usanpn.org

Table 2. Examples of boundary organizations to facilitate coproduction of science knowledge and its use in decision-making.

Similarly, research has documented various ways in which boundary organizations foster relationship building and knowledge exchange to increase awareness of the predictable impacts of climate variability on water and natural resource management, as well as understanding of forecast confidence (Dilling and Lemos 2011; McNie 2013). The work documented by these researchers, in the US Southeast and Pacific Northwest, resulted in the application of basic and applied science insights to water management actions and emergency preparedness.

Purposeful engagement between basic research scientists and decision makers, again through boundary organizations, has also resulted in substantial operations and policy changes, based on insights coming from projections and reconstructions of decade-to-century scale change. For example, New York City's climate adaptation plan, credited with partly reducing vulnerability of coastal infrastructure during Hurricane Sandy, was based on the translation of climate model projections to recommendations deemed actionable by policy makers (Horton et al. submitted). And in the western US, basic research insights from paleoclimate reconstructions of streamflow have been adopted by water management agencies as the basis of changes to operational planning, drought emergency preparedness, and preparations for future climate changes (Phillips et al. 2009; Rice et al. 2009; Woodhouse and Lukas 2006).

In these instances, and many others, iterative interactions between researchers and management practitioners have been essential to establishing the knowledge needed to translate jargon, circumvent constraints, and sufficiently align research and policy goals. These studies also illustrate the occasional need to involve basic science researchers in the process in order to establish the credibility of the science, establish that the results were actionable, and answer methodological questions posed by the technical staff of decision-making entities.

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TRANSITIONS

Welcome New US CLIVAR Scientific Steering Committee Members

The US CLIVAR Scientific Steering Committee (SSC) welcomes new members who will join the leadership ranks in 2015. The new members include SSC Executive Committee co-chair Sonya Legg (Princeton University), POS Panel co-chair Art Miller (Scripps Institution of Oceanography), PSMI Panel co-chair Caroline Ummenhofer (Woods Hole Oceanographic Institution), and PPAI Panel co-chair Kathy Pegion (George Mason University). The role of the SSC is to provide overall scientific and programmatic guidance for the program, develop science plans, and implements strategies to ensure the US CLIVAR progresses towards achieving its science goals. Membership is comprised of community leaders with broad expertise.

A big thanks for their years of service goes out to Janet Sprintall (Scripps Institution of Oceanography), Dimitris Menemenlis (NASA Jet Propulsion Laboratory), Tom Farrar (Woods Hole Oceanographic Institution), and Bruce Anderson (Boston University).

Welcome New US AMOC Executive Committee Members

The US AMOC Executive Committee welcomes new members who joined the leadership ranks in October. The new members include Task Team 1 vice-chair Renellys Perez (University of Miami/NOAA Atlantic Oceanographic Meteorological Laboratory), Task Team 2 vice-chair Alicia Karspeck (National Center for Atmospheric Research), and Task Team 4 vice-chair Andreas Schmittner (Oregon State University). As Executive Committee members, they are charged with surveying the state of knowledge and setting long-term program objectives, identifying scientific gaps and research needs, encouraging and coordinating research activities, and reporting on the state of the science, program progress, and future prioirities.

The following members have rotated off after two-years of service on the Executive Committee: Patrick Heimbach (Massachussets Institute of Technology), Yochanan Kushnir (Columbia University/Lamont-Doherty Earth Observatory), and Rong Zhang (NOAA Geophysical Fluid Dynamics Laboratory). There dedication and committment is greatly appreciated.

Call for New US CLIVAR Panel Members

In January, the US CLIVAR Scientific Steering Committee will announce a call for qualified individuals to join the three Panels (POS, PSMI, and PPAI). Nominees are expected to represent the broad interests of the research community and be willing to engage in scientific and programmatic discussions. Details about the SSC and Panels can be found **online**. Stay tuned for more details.

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